# The Discovery of Electron Waves *

By C. J. DAVISSON

THAT streams of electrons possess the properties of beams of waves was discovered early in 1927 in a large industrial laboratory in the midst of a great city, and in a small university laboratory overlooking a cold and desolate sea. The coincidence seems the more striking when one remembers that facilities for making this discovery had been in constant use in laboratories throughout the world for more than a quarter of a century. And yet the coincidence was not, in fact, in any way remarkable. Discoveries in physics are made when the time for making them is ripe, and not before; the stage is set, the time is ripe and the event occurs—more often than not at widely separated places at almost the same moment.

The setting of the stage for the discovery of electron diffraction was begun, one may say, by Galileo. But I do not propose to emulate the gentleman who began a history of his native village with the happenings in the Garden of Eden. I will take, as a convenient starting point, the events which led to the final acceptance by physicists of the idea that light for certain purposes must be regarded as corpuscular. This idea after receiving its quietus at the hands of Thomas Young in 1800 return to plague a complacent world of physics in the year 1899. In this year Max Planck put forward his conception that the energy of light is in some way quantized. A conception which, if accepted, supplied, as he showed, a means of explaining completely the distribution of energy in the spectrum of black body radiation. The quantization was such that transfers of energy between radiation and matter occurred abruptly in amounts proportional to the radiation frequency. The factor of proportionality between these quantities is the ever-recurring Planck constant, $h$. Thus was reborn the idea that light is in some sense corpuscular.

How readily this circumstantial evidence for a corpuscular aspect of light would have been accepted as conclusive must remain a matter of conjecture, for already the first bits of direct evidence pointing to the same conclusion were being taken down from the scales and meters of

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the laboratory; the truth about light was being wrung from Nature—at times, and in this case, a most reluctant witness.

In an extended examination carried on chiefly by Richardson and K. T. Compton, Hughes, and Millikan, it was brought out that light imparts energy to individual electrons in amounts proportional to its frequency and finally that the factor of proportionality between energy and frequency is just that previously deduced by Planck from the black body spectrum. The idea of pressing the witness on the latter point had come from Einstein who out-plancked Planck in not only accepting quantization, but in conceiving of light quanta as actual small packets or particles of energy transferable to single electrons in toto.

The case for a corpuscular aspect of light, now exceedingly strong, became overwhelmingly so when in 1922 A. H. Compton showed that in certain circumstances light quanta—photons as they were now called—have elastic collisions with electrons in accordance with the simple laws of particle dynamics. What appeared, and what still appears to many of us as a contradiction in terms had been proved true beyond the least possible doubt—light was at once a flight of particles and a propagation of waves; for light persisted, unreasonably, to exhibit the phenomenon of interference.

Troubles, it is said, never come singly, and the trials of the physicist in the early years of this century give grounds for credence in the pessimistic saying. Not only had light, the perfect child of physics, been changed into a gnome with two heads—there was trouble also with electrons. In the open they behaved with admirable decorum, observing without protest all the rules of etiquette set down in Lorentz's manual, but in the privacy of the atom they indulged in strange and unnatural practices; they oscillated in ways which no well-behaved mechanical system would deem proper. What was to be said of particles which were ignorant apparently of even the rudiments of dynamics? Who could apologize for such perversity—rationalize the data of spectroscopy? A genius was called for, and a genius appeared. In 1913 Niels Bohr gave us his strange conception of "stationary" orbits in which electrons rotated endlessly without radiating, of electrons disappearing from one orbit and reappearing, after brief but unexplained absences, in another. It was a weird picture—a picture to delight a Surrealist—but one which fascinated the beholder, for in it were portrayed with remarkable fidelity the most salient of the orderly features which spectroscopic data were then known to possess; there was the Balmer series! and there the Rydberg constant!—correct to the last significant digit! It was a masterpiece. It is important to

note that in achieving this *tour de force* Bohr made judicious use of the constant which Planck had extracted from the black body spectrum, the constant $h$.

It looked at this time—in the year 1913—as if the authentic key to the spectra had at last been found, as if only time and patience would be needed to resolve their riddles completely. But this hope was never fulfilled. The first brilliant triumphs of the theory were followed by yet others, but soon the going became distressingly difficult, and finally, despite the untiring efforts of countless helpers, the attack came virtually to a standstill. The feeling grew that deeply as Bohr had dived he had not, so to speak, touched bottom. What was wanted, it was felt, was a new approach, a new theory of the atom which would embrace necessarily all the virtues of the Bohr theory and go beyond it —a theory which would contain some vaguely sensed unifying principle which, it was felt, the Bohr theory lacked.

Such an underlying principle had been sought for almost from the first. By 1924 one or two ideas of promise had been put forward and were being assiduously developed. Then appeared the brilliant idea which was destined to grow into that marvelous synthesis, the present day quantum mechanics. Louis de Broglie put forward in his doctor's thesis the idea that even as light, so matter has a duality of aspects; that matter like light possesses both the properties of waves and the properties of particles. The various "restrictions" of the Bohr theory were viewed as conditions for the formation of standing electron wave patterns within the atom.

Reasoning by analogy from the situation in optics and aided by the clue that Planck's constant is a necessary ingredient of the Bohr theory, de Broglie assumed that this constant would connect also the particle and wave aspects of electrons, if the latter really existed. De Broglie assumed that, as with light, the correlation of the particle and wave properties of matter would be expressed by the relations:

(Energy of particle) $E = h\nu$ (frequency, waves/unit time).
(Momentum of particle) $p = h\sigma$ (wave number, waves/unit distance).

The latter may be written in the more familiar form $\lambda = h/p$ where $\lambda$ represents wave-length.

Perhaps no idea in physics has received so rapid or so intensive development as this one. De Broglie himself was in the van of this development but the chief contributions were made by the older and more experienced Schroedinger.

In these early days—eleven or twelve years ago—attention was focussed on electron waves in atoms. The wave mechanics had

sprung from the atom, so to speak, and it was natural that the first applications should be to the atom. No thought was given at this time, it appears, to electrons in free flight. It was implicit in the theory that beams of electrons like beams of light would exhibit the properties of waves, that scattered by an appropriate grating they would exhibit diffraction, yet none of the chief theorists mentioned this interesting corollary. The first to draw attention to it was Elsasser, who pointed out in 1925 that a demonstration of diffraction would establish the physical existence of electron waves. The setting of the stage for the discovery of electron diffraction was now complete.

It would be pleasant to tell you that no sooner had Elsasser's suggestion appeared than the experiments were begun in New York which resulted in a demonstration of electron diffraction—pleasanter still to say that the work was begun the day after copies of de Broglie's thesis reached America. The true story contains less of perspicacity and more of chance. The work actually began in 1919 with the accidental discovery that the energy spectrum of secondary electron emission has, as its upper limit, the energy of the primary electrons, even for primaries accelerated through hundreds of volts; that there is, in fact, an elastic scattering of electrons by metals.

Out of this grew an investigation of the distribution-in-angle of these elastically scattered electrons. And then chance again intervened; it was discovered, purely by accident, that the intensity of elastic scattering varies with the orientations of the scattering crystals. Out of this grew, quite naturally, an investigation of elastic scattering by a single crystal of predetermined orientation. The initiation of this phase of the work occurred in 1925, the year following the publication of de Broglie's thesis, the year preceding the first great developments in the wave mechanics. Thus the New York experiment was not at its inception, a test of the wave theory. Only in the summer of 1926, after I had discussed the investigation in England with Richardson, Born, Franck and others, did it take on this character.

The search for diffraction beams was begun in the autumn of 1926, but not until early in the following year were any found—first one and then twenty others in rapid succession. Nineteen of these could be used to check the relationship between wave-length and momentum and in every case the correctness of the de Broglie formula, $\lambda = h/p$ was verified to within the limit of accuracy of the measurements.

I will recall briefly the scheme of the experiment. A beam of electrons of predetermined speed was directed against a (111) face of a crystal of nickel as indicated schematically in Fig. 1. A collector designed to accept only elastically scattered electrons and their near

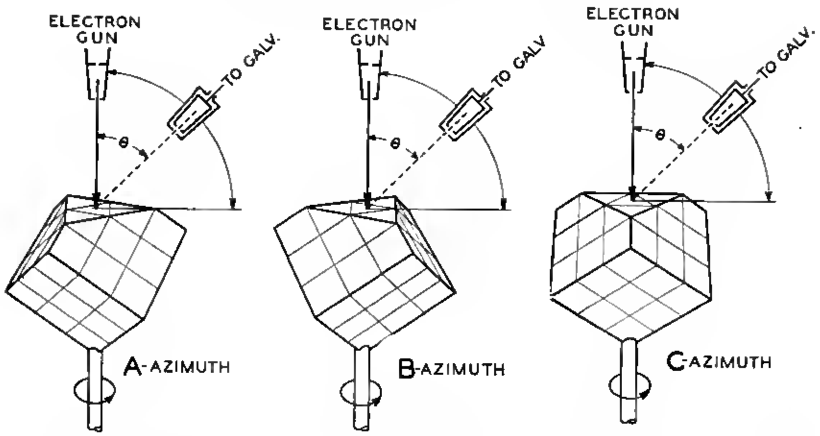


Fig. 1—Schematic diagram showing disposition of primary beam, nickel crystal and collector. Crystal shown revolved to bring one principal azimuth after another into plane of observation.

neighbors, could be moved on an arc about the crystal. The crystal itself could be revolved about the axis of the incident beam. It was possible thus to measure the intensity of elastic scattering in any direction in front of the crystal face with the exception of those directions lying within 10 or 15 degrees of the primary beam.

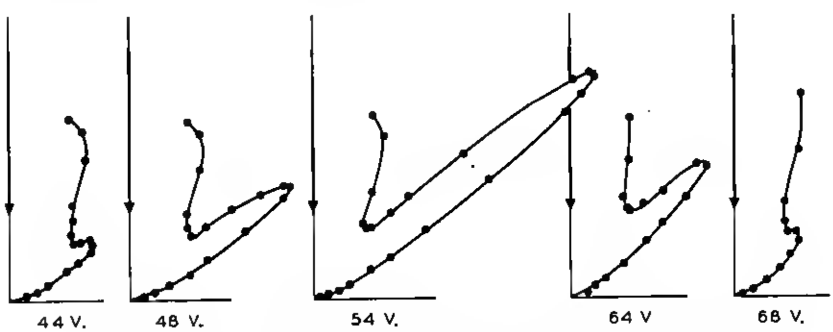


Fig. 2—Polar diagram showing intensity of elastic scattering in A-azimuth (see Fig. 1) as function of latitude angle, for series of primary beam voltages.

The curves reproduced in Fig. 2 show the distribution-in-angle of intensity for a particular azimuth of the crystal. The curves are for a series of electron speeds, therefore, for a series of electron wave-lengths. For a particular wave-length a diffraction beam shines out. Setting the collector on this beam at its brightest and revolving the crystal, the intensity was found to vary in azimuth as illustrated in Fig. 3.

The high peak on the left represents the cross-section-in-azimuth of the beam shown in Fig. 2. Two similar peaks mark the positions of companion beams which with the first form a set of three, as required by the threefold symmetry of the crystal about its (111) directions—the direction of the incident beam. The lesser intermediate peaks are due to a different set of beams which is not here fully developed.

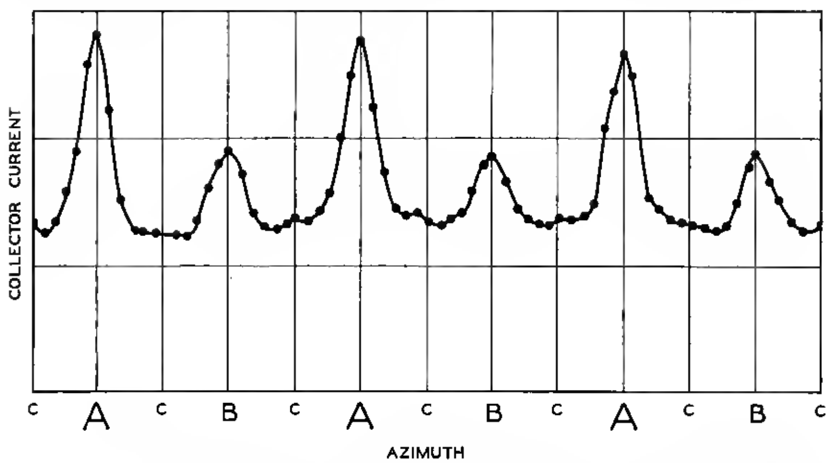


Fig. 3—Curve showing intensity of elastic scattering of 54-volt primary beam as function of azimuth for latitude of peak in 54-volt curve, Fig. 2.

The de Broglie relation was tested by computing wave-lengths from the angles of the diffraction beams and the known constant of the crystal, and comparing these with corresponding wave-lengths computed from the formula $\lambda = h/p$, where $p$, the momentum of the electrons, was obtained from the potential used to accelerate the beam and the known value of e/m for electrons. If wave-lengths computed from the formula agreed with those obtained from the diffraction data, the de Broglie relation would be verified. How nearly the theoretical values agreed with the experimental is illustrated in Fig. 4. For perfect agreement all points would fall on the line drawn through the origin.

You will realize without my telling you that this series of experiments extending in time over a period of eight or nine years and requiring the construction and manipulation of intricate apparatus was not made by me alone. From first to last a considerable number of my colleagues contributed to the investigation. Chief among these were my two exceptionally able collaborators, Dr. C. H. Kunsman and Dr. L. H. Germer. Dr. Kunsman worked with me throughout the early stages of the investigation, and Dr. Germer, to whose skill and perseverance

a great part of the success of the definitive experiments is due, succeeded Dr. Kunsman in 1924.

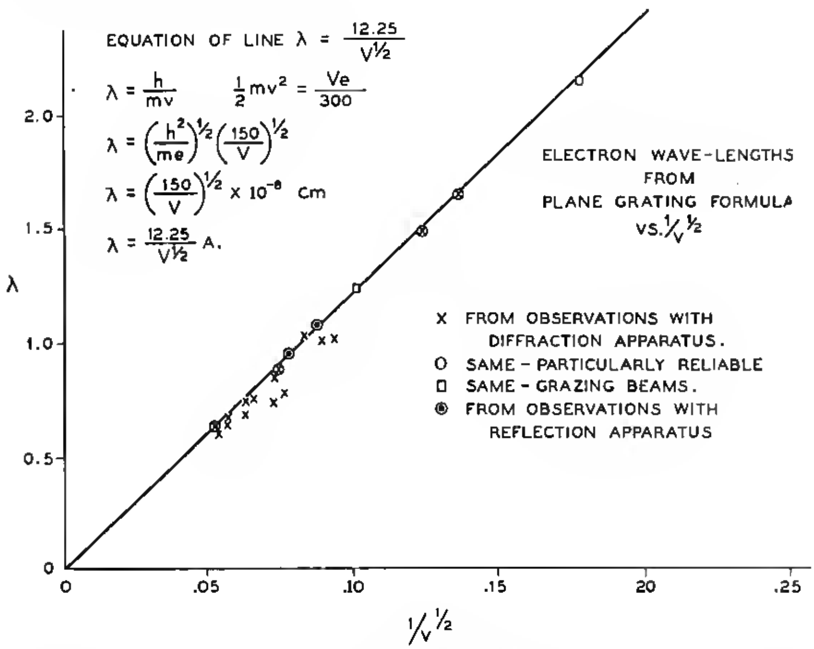


Fig. 4—Test of the de Broglie formula $\lambda = h/p = h/mv$. Wave-length computed from diffraction data plotted against $1/V^{1/2}$, ($V$, primary beam voltage). For precise verification of the formula all points should fall on the line $\lambda = 12.25/V^{1/2}$ plotted in the diagram.

I would like also at this time to express my admiration of the late Dr. H. D. Arnold, then Director of Research in the Bell Telephone Laboratories, and of Dr. W. Wilson, my immediate superior, who were sufficiently far-sighted to see in these researches a contribution to the science of communication. Their vision was, in fact, accurate for today in ours, as in other industrial laboratories, electron diffraction is applied with great power and efficacy for discerning the structures of materials.

But neither of this nor of the many beautiful and important researches which have been made in electron diffraction in laboratories in all parts of the world since 1927 will I speak today. I will take time only to express my admiration of the beautiful experiments—differing from ours in every respect—by which Thomson in far-away Aberdeen also demonstrated electron diffraction and verified de Broglie's formula at the same time as we in New York. And to mention, as

closely related to the subject of this discourse, the difficult and beautifully executed experiments by which Stern and Esterman in 1929 showed that atomic hydrogen also is diffracted in accordance with the de Broglie-Schroedinger theory.

Important and timely as was the discovery of electron diffraction in inspiring confidence in the physical reality of material waves, our confidence in this regard would hardly be less today, one imagines, were diffraction yet to be discovered, so great has been the success of the mechanics built upon the conception of such waves in clarifying the phenomena of atomic and subatomic physics.